METEOR RESEARCH PROGRAM

SEMIANNUAL TECHNICAL REPORT NO. 8

Contract NSR 09-015-033

July 1 to December 31, 1969

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Prepared for
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1. INTRODUCTION

Progress Reports for the Meteor Research Program are generally directed toward a specific recent result. While this may serve the purpose of keeping the constant reader appraised of the progress, it does little to aid in the assessment of the more important progress required to provide a self-consistent picture of the nature and origin of the stray bodies of the solar system and of their interaction with our atmosphere. Therefore, in this report we attempt to present a unified view of much of the work of the past several years. Because of the large number of important new insights acquired in the last year, it is now particularly appropriate to make this review.

1.1 The Past Year

The highlights of the Meteor Research Program during the past year include

A. The discovery that recombination is important for many radar meteors; this revises our values of ionizing probability and clarifies the physical behavior.

B. The discovery that most of even the smallest radar meteors fragment in flight, showing that they are fragile and probably of low density.

C. The discovery of meteor streams associated with the "Apollo" (earth-crossing) asteroids.

D. The first simultaneous radar-optical observations of faint meteors; these will yield the first reliable calibration of the masses of radar meteors from the masses of optical meteors.

E. The first observed spectra of faint optical meteors, showing that physical processes differ between bright and faint meteors.

F. The detection of atmospheric gravity waves by radar observations of meteors.

G. The discovery of a theoretical technique for computing rates of particle interactions at meteoric energies; we expect this to be of the greatest value because hardly any theoretical or laboratory values have heretofore been available.

1.2 The Past Decade

In the past decade, the astronomical physics of meteors has enjoyed a number of noteworthy advances, and the way has been paved for more innovations in the near future. These are results from new observations with new instrumentation, new theories, and a new and healthy sense of ignorance about some problems that had previously been considered resolved. The importance of the last of these, resulting from the others, should not be underestimated. The short lifetimes of meteorites after their last fragmentation from a parent body have been derived from isotopic studies of meteorites; these lifetimes seem inconsistent with an asteroidal origin of this material. Some investigators consider comets a more likely source. In this same vein, an investigation of radar meteor orbits suggests that the Apollo-type asteroids may have meteor showers associated with them and thus display one of the frequent characteristics of comets. Radar meteor orbits further show that relatively rapid processes for changing orbit distributions need to be identified. Ideas on the character and quantity of large meteoroids have undergone considerable change. The new results bear heavily on the interpretation of lunar and Martian craters. At the extreme faint end of the observable — the radar meteors — new information on the effects of fragmentation of the meteoroid and recombination rates in the electron column is forcing a major reevaluation of earlier analyses. Spectra of very faint meteors obtained in the past year show new radiation characteristics that will require a reevaluation of some earlier work and offer a new form of information bearing on the physical theory of meteors.

The substantial advances in instrumentation and observations include free-flight artificial-meteor experiments, a powerful and multistation calibrated radar array, image-orthicon systems for the optical observations of very faint meteors, and a multistation network for observations of rare, bright objects.

The theory of meteors has expanded as a result of reentry studies. Detailed investigations on the behavior of materials under these conditions have been made and applied to the meteor problem.

1.3 Organization of this Report

In this report we have divided the problems and progress in the field of meteors into four categories: spacecraft engineering and the meteoroid hazard, physical theory of meteors, meteor astronomy, and atmospheric phenomena. This division is quite arbitrary in that no aspect can be dealt with adequately without considering the others. For example, a complete description of the meteoroid hazard to spacecraft requires a specification of the distribution of velocities and masses (and probably of material densities) as a function of time of year and position in the solar system. Mass is not a directly measured quantity in any meteor observation and must be inferred with the aid of an adequate physical theory. The same is true of meteoroid densities. Velocities are easily obtained by both radar and optical techniques, but the observational biases of any system can be corrected only if a theory is available that describes the magnitude of a meteor event for a given meteoroid mass and velocity. Biases introduced by variations in the atmosphere are possible and should be considered. Extrapolations to regions of space outside the earth's orbit cannot be made without recourse to some astronomical considerations that include, among other things, the distribution of comets and asteroids in addition to fundamental information on the relative importance of each of these classes of objects as parent bodies for meteors.

In the following summary of results obtained by the Meteor Research Group at Smithsonian Astrophysical Observatory (SAO), we have assigned each major result to the category that appears to us to describe most reasonably the nature of the work.

2. SPACECRAFT ENGINEERING AND THE METEOROID HAZARD

2.1 Progress

The Smithsonian Meteor Research Programs and their predecessors, the Harvard Meteor Programs, have supplied virtually all the velocity distribution and mass flux data for meteors in the range 10 to 10^{-4} g. The radar observations apply directly to the size of meteoroids believed to be the principal hazard to space missions now being planned. With the exception of the early work by Whipple on the meteoroid bumper concept, we have concentrated our efforts almost entirely upon determination of the distribution and flux rather than on the specific engineering problem of damage caused by meteoroids. The basic data on optical meteors in the mass range from 10 to 10^{-2} g (Whipple, 1954; Hawkins and Southworth, 1958, 1961; McCrosky and Posen, 1961; Jacchia and Whipple, 1961; Jacchia, Verniani, and Briggs, 1965) have been treated extensively by many investigators. The primary calibration for mass of these meteoroids was accomplished by a joint NASA-Smithsonian meteor-simulation project.

Radar data have been collected with a fully calibrated radar system for 15 months, and provisional flux values deduced from earlier results were given by Nilsson and Southworth (1967). Data in hand will eventually establish an improved value of the flux of radar meteors that should have a substantially smaller probable error. Most of the problems standing in the way of an immediate definitive expression of the flux for radar meteors are best covered in the following sections, but we list them here for completeness.

2.2 Problems

A. The ionization-mass relationship has, in the past, been estimated from scanty and misleading data (Verniani and Hawkins, 1964). It should be considered the major known uncertainty in the analysis of the radar records.

Initial results of simultaneous observations between radar and image-orthicon (optical) meteors strongly suggest that significantly more accurate ionization probabilities for meteors can be had from a calibration via the comparatively well-known relation between luminosity, mass, and velocity.

B. The effects of fragmentation and recombination of the ion column are evident in the radar Fresnel-pattern records. This result is directly attributable to the calibration of the radar system and its antennas, which permitted us to accept, as real, certain characteristics that we might otherwise have considered artifacts of the observing system. Statistical analysis of a large number of radar meteors and detailed studies of a smaller number are required to understand these two phenomena in greater detail. The anomalous nature of the Fresnel patterns produced by these effects will certainly increase the task of reducing the radar data. Some changes in software will be required.

C. The bias of radar observations for meteors of very low and very high velocity is not satisfactorily known. Simultaneous optical and image-orthicon observations are required.

D. The year-to-year variations in the radio meteor flux observed in Australia and in Canada demand an explanation of whether the cause is astronomical, atmospheric, or instrumental. If the cause is not instrumental, the flux will need further corrections.

3. PHYSICAL THEORY OF METEORS

3.1 Mass

It was something of an embarrassment to the meteor astronomer that such a fundamental quantity as the mass of the object he studied was almost unknown 10 years ago. There is a clear, and expected, relationship between mass and either luminosity or ionization, but the precise relationship between the quantities could not be determined so long as either the structure of the body or its behavior during atmospheric entry remained unknown. At one time, the mass of meteors was overestimated by nearly 2 orders of magnitude by studies of meteor trains and, at the same time, underestimated by nearly 2 orders of magnitude by oversimplified dynamical considerations applied to a particular meteorite. A reliable basepoint for the mass-to-luminosity relationship has now been established by the NASA-Smithsonian meteor-simulation experiments.

3.2 Structure and Density

We can reasonably suppose that for meteors of +3 to -3 mag, the mass error for all velocities does not exceed a half order of magnitude. This new knowledge has permitted us to investigate, with far greater confidence than previously, the structure and ablation process of meteoroids. The measured deceleration of optical meteors and the rate of change of deceleration are consistent, by and large, with bodies of low density (0.3 to 1 g/cc) that have little structural integrity and continually disintegrate by gross fragmentation as they proceed deeper into the atmosphere. Alternative explanations of the observed data have been given by Allen and Baldwin and by Jones and Kaiser. The former authors envisage a high-density meteoroid behaving as though it were low density because of the production of froth on the leading surface during ablation process. Jones and Kaiser call upon the thermal shock to disrupt a high-density stone into a number of fragments that, they say misleads one when deriving a ballistic coefficient from the observed drag. Recent work by McCrosky and Ceplecha on very large and very bright objects suggests that neither frothing nor thermal shock can be important for bodies of radius greater than 10 cm. But even these large bodies display the characteristics of low-density objects, and they conclude that progressive fragmentation of fragile objects is the most likely explanation for the behavior of nearly all photographic meteors.

A very few photographic meteors behave in the way expected of a stronger high-density object. When these are analyzed under the assumption that they are similar to stony meteorites, the mass-luminosity function derived from the artificial meteor experiments is verified.

3.3 Spectra

The fundamental observation that has permitted us to associate meteor luminosity with meteor mass (rather than, for example, meteoroid size or atmospheric density) is the nearly complete predominance of meteoric line radiation in meteor spectra. Observations currently being made by two different systems are supplying evidence that will require us to adjust the simple theory when applied to faint meteors. The first system is a bank of fast meteor spectrographs operated by Smithsonian for NASA/Langley Research Center (LRC). Gail Harvey of LRC finds that the relative intensity of the H and K lines of ionized calcium with respect to the rest of the spectrum shows an enhancement as the total meteor luminosity increases. There must, therefore, be some additional intensity function in the mass-luminosity relationship that is not currently accounted for in the simple theory.

A second observing system consists of an image-orthicon spectrograph of the Dudley Observatory operating in conjunction with a meteor radar in Canada. Early results from this system have been analyzed by Hemenway of Dudley, Millman of the National Research Council of Canada, and Cook of

SAO. The existence of two distinct types of spectra in faint meteors is found. In one, the usual atomic line radiation predominates, and in the other, appreciable quantities of band or continuum radiation are observed. It is evident that these two classes of meteors will exhibit different luminous efficiencies. Continuation of the spectral analysis program promises to open a path to understanding this behavior and will thus feed back in a vital way to the calibration of the radar and image-orthicon observations.

Identification of ionized atmospheric molecules as the cause of recombination in the radar data is a further clue to the understanding of faint meteors.

3.4 Atomic Theory

Ionization and excitation cross sections in the meteoric process are being studied by Flannery and Levy of SAO. This represents the first sustained effort to study the details of the pertinent atomic processes by purely theoretical considerations. The first results have appeared in a series of papers (Flannery, 1968, 1969a-d, 1970a-f; Flannery and Levy, 1969a, b, 1970; Levy, 1969a-d, 1970). Within the past few months, Flannery has succeeded in formulating the exact classical theory for interactions of ionization and excitation during collision of any atomic particles. This is certainly to be regarded as a major breakthrough, although because of the inherent complexity of the problem, the full ramifications may not be known for many months. We hope that this advance will provide vital aid in the interpretation of the results of the two programs on spectral analysis.

The new information on fragmentation and recombination referred to in the previous section is discussed by Southworth (1969). These results, though making the analysis of the radar data more difficult, have served to remove roadblocks that had stultified any progress in the physical theory of radar meteors for a number of years.

3.5 Ablation

As the uncertainties of mass and density of meteoroids decrease, it becomes increasingly possible and useful to concentrate attention on the mode of ablation of the meteoroids. A study of selected Super-Schmidt meteors – those showing little or no fragmentation – is being made by Cook to establish closer limits on the mass-loss parameter, one of the observables in photographic meteors.

More careful attention is being given to the disruptive processes of large meteoroids and the resultant strewn fields of meteorites (such as the great meteorite fall in Pueblito de Allende in 1969). Conclusions on the gross strength of the preatmospheric meteoroid may supply some qualitative limits on the nature of the previous collision history of these bodies in space.

By what must be considered a truly fortuitous set of circumstances, we now have in possession the Lost City meteorite that was recovered, soon after fall, by the Smithsonian Prairie Network. Lost City is an oriented stone; i. e., it has a well-defined leading surface from which most of the ablation must have taken place. Few meteorites have this characteristic. Taken together with the excellent trajectory data available from the photographs, it would appear that we have, in this first recovery, all the information required for a detailed study of the ablation process. Furthermore, collection of ablation debris at 60,000 ft some 18 hours after the event by the Air Force will give more data to aid in the solution of the ablation problem.

3.6 Problems

A. The greatest remaining error in photometric meteor masses is likely to be due to errors in the assumed composition of the material. In theory, meteor spectra contain the information required to calibrate the observations.

B. Further refinements in the photographic luminous-efficiency force for specific classes of meteors may be possible once we have a reliable method of distinguishing these classes.

C. Calibration of the ionizing efficiency for radar meteors remains a prime and immediate goal. A statistically significant number, perhaps 100 or more, of simultaneous observations between radar and image-orthicon systems is a minimum requirement for this task. Very probably we need a larger number to investigate dependence on velocity, and on some of the meteor classes.

A parallel effort to determine the adequacy of our present extrapolation of the photographic luminous efficiency to the much fainter image-orthicon meteors is needed and will require further study of image-orthicon meteor spectra or of image-intensifier meteor spectra.

4. METEOR ASTRONOMY

4.1 History and Origin of Meteors

The ultimate goal of meteor astronomy is easily expressed as knowledge of the history and origin of meteor bodies. Specific problems that may be solvable in the next few years concern the recent history of these bodies, together with an identification of their source. Comets are the indisputable source of many meteors, and their low-density characteristic is a predictable result based on the best physical theory of comets. There has been an almost compulsive desire to associate other types of meteors, and in particular meteorites, with the other stray bodies of the solar system, the asteroids. Jacchia, in a brief history of meteors, has offered a comment about the relationship between comets and meteors that the present-day investigator might well extrapolate to the meteorite-asteroid connection. He says, "Paradoxically as it may seem, one could almost make the assertion that the discovery of a close relationship between meteors and comets became a misleading factor in the search for the physical nature of both classes of celestial bodies. Since practically nothing was known about either of them, the discovery merely established a relationship between two unknowns."

Orbital distributions show that stream meteors originate in comets and that at least most sporadic meteors also originated in comets but have since been perturbed out of their original streams. The smaller sporadics and particularly the radar sporadics, however, have orbits so much smaller and less eccentric on the average than the comets that some additional process besides gravitational perturbation is required to explain them. Collisions are doubtless important (Southworth, 1967; Dohnyani, 1967; Whipple, 1967), but the Poynting-Robertson effect, electromagnetic forces, and cometary activity must all be evaluated.

There is no compelling orbital evidence that any meteors, large or small, originate in the main part of the asteroid belt between Mars and Jupiter. Meteorite orbits and the orbits of Apollo (earth-crossing) asteroids are not similar to those of either main-belt asteroids or comets; and we do not know how these orbits evolved or which source is more likely on orbital grounds.

A very small unidentified proportion of meteors possibly originates in interstellar space or in collisions of large meteors with our moon and other bodies in the solar system that have no atmosphere.

4.2 Classes of Meteors

On a phenomenological basis, we believe at least five classes of meteoroids can be recognized. We include as two of these the iron and the stone meteorites. As fainter meteor spectra have been obtained, the number of objects showing a remarkable absence of sodium has increased. While these may be pure iron-nickel meteoroids, it is currently impossible to reconcile their atmospheric trajectories with this type of material (McCrosky, 1968). This third class of sodium-free meteoroids may then be representative of a source that underwent an unusual chemical differentiation. The distinction between the fourth and the fifth classes lay hidden in the photographic data until unearthed by Ceplecha while at SAO in 1968. (Ceplecha distinguishes between four types of meteors: A, B, C_1, and C_2. For purposes of this discussion the last three classes are lumped together as apparently low-density objects of cometary origin, and Class A is considered a new and unique classification.) The Class A meteors, originallv detected because of their abnormally low beginning heights, are also characterized by low velocity and small orbits. Their density is higher (or their luminous efficiency is lower) than that of the average photographic meteor.

Our understanding of the relationship between comets and meteors is vastly enriched by Cook's discovery that stream meteors associated with known comets are either Class A or Class C, while the parent comets of Class B streams have not been observed. Adopting Whipple and

Stefanik's (1966) model of an icy conglomerate nucleus with radioactive heating and redistribution of ices to the surface, Cook identifies Class A meteoroids with the core of a cometary nucleus and Class C with the less dense surface of the nucleus after sublimation of the ices. Class B is then to be identified with less dense cores of smaller cometary nuclei.

In the above listing, we have not included as a separate category the unusual carbonaceous chondrites of Types I and II, since we suspect that these may be the same as or closely related to Ceplecha's Type A. Carbonaceous chondrites have a density of only about 2 g/cc. Those recovered may be the tough, indurate portion of a body whose overall density might be close to the 1 g/cc suggested for Type A meteors. To carry the speculation further, we wonder if the continuous spectra observed in faint image-orthicon meteors is not the blackbody radiation from soot particles detached from the carbonaceous material, as was suggested earlier by H. Julian Allen.

Our emphasis on this new aspect of meteor astronomy is, we think, compatible with its possible importance for the general study of the evolution and formation of the solar system. If the carbonaceous chondrites are "half-baked" asteroids as suggested by Whipple or if, as also seems possible, they are "overcooked" comets, then in either case they represent the most fundamental and least differentiated material accessible to us now. As such, it should have retained most of the clues concerning the conditions of material early in the history of the solar system.

Sekanina of SAO has recently shown that minor meteor showers may be associated with some of the Apollo asteroids. The next logical step in this particular investigation is to ascertain whether or not these objects have the physical characteristics of the Class A meteors. Since these showers are far too weak to be observed photographically, this important result must await the time when the physical theory of radar meteors has advanced to the point that the analysis of these data will give reliable information on structure.

4.3 Problems

A. We mentioned briefly, and for completeness, the long-standing astronomical problems of celestial mechanics that pertain to comets and asteroids: 1) the Jupiter-barrier problem, in which one seeks an understanding of the means by which the aphelia of comets are reduced to a point inside Jupiter's orbit; and 2) the meteorite-lifetime problem, which requires an (unlikely) means of bringing asteroids to the earth in a few hundred million years or locates the source and origin of earth-crossing bodies that produce present-day meteorites.

B. The evolution of the distribution of meteor orbits under gravitational perturbations, collisions, electromagnetic forces, cometary activity, the Poynting-Robertson effect, and other forces is computable but not yet solved because of inadequate observations. Unbiased radar orbit statistics are the most important current need.

C. A meteoroid hazard in the vicinity of Mars will certainly be raised as an important technical question within the next decade. Given the distribution of comets with perihelia inside the orbit of Mars, a reasonable lower limit to the hazard can be established by extrapolation from the earth-based observations. Southworth (1967) has already made preliminary estimates on the space density of material based on radar meteors and the zodiacal light. We do not foresee any method that will establish the asteroidal flux that may be peculiar to Mars, and we presume that this information will come only from measurements of Mars spacecraft. We have made a preliminary investigation on the requirements of photoelectric sensors on the Martian surface that should be capable of distinguishing between the cometary and asteroidal components. The use of the Martian atmosphere as a meteor counter can have great advantages over a spacecraft measuring puncture damage.

D. We now have under observation those large meteoroids that produce lunar craters in the range of tens of meters. There still remains some question of the mass calibration for these very large objects; and we are not yet certain whether the Prairie Network data will provide reliable flux measures for the interpretation of the lunar landscape or whether lunar craters will provide a calibration for us.

5. ATMOSPHERIC PHENOMENA

Meteors were originally used as probes of the upper atmosphere when knowledge of that environment was even poorer than that about the meteoroids. Fortunately for the meteor astronomer, the situation was reversed 20 years ago with the advent of sounding rockets. The usefulness of meteors in this regard today remains only because of the high frequency of the events.

5.1 Winds and Gravity Waves

It is possible to measure the horizontal wind field from the displacement of the meteor ion column. The Smithsonian radar facility is designed to make such measures. Gravity waves in the upper atmosphere have also been investigated by an extension of this technique.

5.2 Density and Temperature

It has been expected that radar meteor observations would be able to measure density and temperature (scale-height) variations in the atmosphere, but results to date have been quite unsatisfactory. We now realize that all existing analyses were vitiated by unrecognized recombination in the electron columns. Corrections for recombination are possible, in principle, for meteors observed with our equipment but not for most other observations. We do not yet know whether useful measures of density and temperature can be made in practice.

5.3 Atomic Oxygen

The spectra observed by the image-orthicon technique show the auroral green line of metastable atomic oxygen as a universal feature for high-velocity meteors and a common feature for slower meteors. Since this line must be due to excitation of atmospheric oxygen, the spectral observations yield new information on its distribution.

5.4 Meteor Rate Changes

Australian and Canadian meteor astronomers (Ellyett and Keay, 1964; McIntosh and Millman, 1964; Lindblad, 1967) have reported significant year-to-year variations in the influx of radar meteors. If the cause is not in their equipment, it must be somewhere in the atmosphere or ionosphere because the spread of orbital periods does not permit any such variation outside the sphere of influence of the earth. One explanation not yet disproved is variations in atmospheric scale height, which we will attempt to detect.

Any geophysical explanation of the variations may necessitate further corrections to our measures of meteor influx.

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